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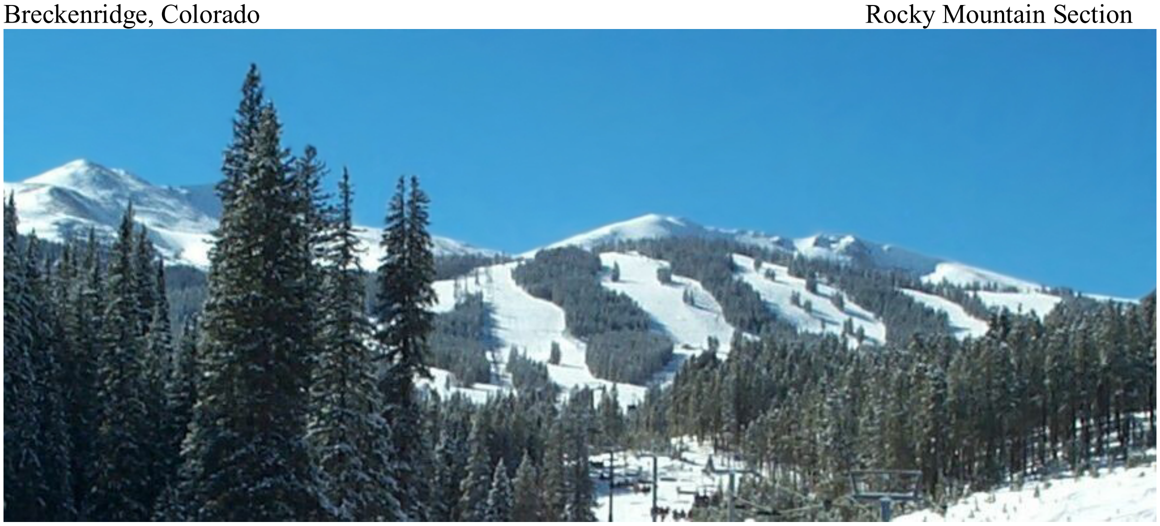

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COMPARING PRE-LAUNCH ASSUMPTIONS TO IN-FLIGHT NAVIGATION PERFORMANCE FOR OSIRIS-REX

Peter G. Antreasian,[*] Coralie D. Adam,[*] Kevin E. Berry,[†] Jeroen L. Geeraert,[*] Kenneth M. Getzandanner,[†] Dolan E. Highsmith,[‡] Jason M. Leonard,[*] Erik Lessac-Chenen,[*] Andrew Levine,[*] Jim V. McAdams,[*] Leilah K. McCarthy,[*] Michael C. Moreau,[§] Derek S. Nelson,[*] Brian R. Page,[*] John Y. Pelgrift,[*] Samantha Rieger,[†] Eric M. Sahr,[*] Daniel R. Wibben,[*] Bobby Williams,[*] Kenneth E. Williams,[*] and Dante S. Lauretta[¶]

The Sample Return Capsule (SRC) onboard the NASA Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft is currently carrying samples of the B-type asteroid Bennu for safe return to Earth at the Utah Test and Training Range on September 24, 2023. These samples were collected during the Touch And Go (TAG) sampling event on October 20, 2020, when the spacecraft contacted the surface for a few seconds at a location less than 1 meter from the target. The unprecedented navigation performance achieved during that event was the culmination of experience gained during two years of cruise and two years of increasingly challenging operations at Bennu. As we had hoped, the proximity navigation performance at Bennu exceeded pre-launch analysis. This paper will compare the navigation performance through the proximity operation phases to our pre-launch analysis and will quantify how refinements of the small force models governing the spacecraft motion near Bennu considerably improved the down-track state predictions leading up to the successful TAG event. It was evident to the team and to expert peer reviewers during the design phase that exquisite model fidelity and aggressive operational concepts, which challenged and advanced the state of the art for deep space proximity operations, would be required to meet the mission's objectives. This paper summarizes the superlative achievements of the team in rising to and overcoming these challenges.

INTRODUTION

The Sample Return Capsule (SRC) onboard the NASA Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft (S/C) is currently carrying samples of the B-type asteroid (101955) Bennu to be safely returned to Earth and released for landing and recovery at the Utah Test and Training Range (UTTR) on September 24, 2023. These samples were collected during the Touch-and-Go (TAG) sampling event on October 20, 2020, when the S/C contacted the surface for a few seconds at a location less than 1 meter from the target.[1]

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The unprecedented navigation performance achieved during that event was the culmination of experience gained during two years of cruise and two years of increasingly challenging operations at Bennu.[2] As we had hoped, the proximity navigation performance at Bennu exceeded pre-launch analysis.[3–5]

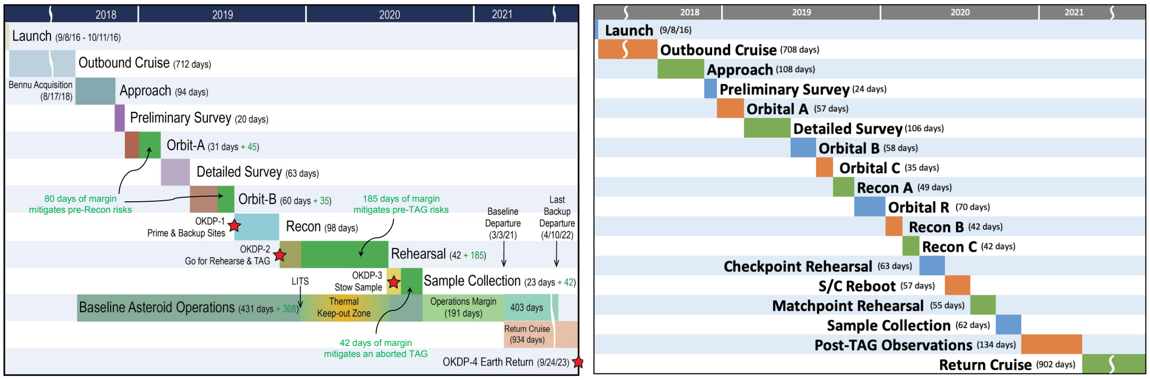
Prior to the encounter with Bennu, significant uncertainty existed regarding the mass of Bennu and its geophysical characteristics. In addition, it was unclear how to assess the S/C performance with respect to requirements which included significant conservatism. Pre-launch navigation analysis based on these conservative assumptions featured large prediction errors, which made science planning difficult and command sequencing complex. It was impossible for scientists to plan site-specific observations when the predicted navigation errors would show that the S/C orbital position would be largely unknown after a few days. This led to the 24-hour 'late update' process for maneuver design and implementation and S/C ephemeris builds. 24-hours was the available window of time between the receipt of new downlink telemetry from the spacecraft to the uplink of the updated command products before maneuver execution and the science data collection. During this time the navigation team had to download the latest images, complete the optical navigation (OpNav) and orbit determination (OD) processing, design the maneuver, then hand off to the S/C team for maneuver implementation.[2,6] The S/C team had to test and verify the command sequence, build the S/C ephemeris, and upload to the S/C. This tight timeline was required so that the onboard sequenced observations would point at the desired asteroid location and the maneuver would execute at the correct location relative to Bennu.[4]

The team improved the navigation predictions starting late in the Approach phase and early proximity operations (ProxOps). During this time, better modeling of the small forces (such as ray-traced solar radiation pressure models) were developed and the S/C thermal re-radiation force model was tuned.[7] The accuracy of the center-finding OpNav and the landmark observations of Bennu improved this effort more than radio-metric tracking data alone.

The actual mission plan and trajectory design of the ProxOps changed from pre-launch to improve navigation, relax schedules, maximize science or reduce operations. For example, these changes included adding two weeks to Approach phase to ventilate operations schedule and adding two extra north polar legs to the Preliminary Survey to improve S/C state errors before first science observations. Regardless of these changes the navigation concept of operations changed very little, as the 24-hr late update build/uplink process for maneuver designs, onboard ephemeris and science observation timing that was planned pre-launch was still implemented in operations to keep the predicted S/C state errors as small as possible. This paper will compare the in-flight navigation performance against pre-launch analysis through the proximity operation phases. We will quantify how refinements of the small force models governing the spacecraft motion near Bennu considerably improved the down-track state predictions over pre-launch expectations leading up to the successful TAG event.

MISSION CHANGES

Development of the ProxOps mission timeline continued after launch and then in ProxOps as the finer details of accomplishing the end goal of capturing 60 g of Bennu's regolith without burning out the Flight Dynamics System (FDS), Science Processing Operations Center (SPOC) and Lockheed Martin (LM) S/C teams became more apparent. As such, time was added to portions of the originally planned initial phases of the mission at Bennu shown in the pre-launch ProxOps schedule in Figure 1a. This baseline plan scheduled TAG towards the end of 2019 before the 'thermal



(a) Pre-launch Proximity Operations Schedule

(b) As-flown Proximity Operations Schedule

Figure 1: Comparing Pre-launch to As-flown Proximity Operations Schedule

keep out zone' during Bennu periapsis when the asteroid-Sun distance could affect the quality of the collected sample because heating of the sample would cause volatiles to escape. This keep out zone extended through the first quarter of 2020. This schedule included margin in several phases to ensure the goals of those phases could be met before moving to the next phase. It also included significant schedule margin for TAG before the S/C could leave the asteroid in March 2021, which was the earliest departure time based on ΔV cost. As such, in the post-launch planning, time was added to the Approach, Preliminary Survey, Orbital-A and Detailed Survey phases.[2] An additional reconnaissance phase (Recon A) was added in late 2019 in response to the dearth of suitable TAG sites, to collect additional data to inform the final TAG site selection. Additional phases such as Orbital C and Orbital R were added in 2019 to allow some reduced activities for the teams after the previous busy schedules as well as to add time for the scientists to process the data to build detailed Digital Terrain Map (DTM)s, global thematic maps (sampleability, deliverability, and safety) for selection of primary and backup sites. These changes are discussed by Antreasian, et al..[2] Figure 1b shows the as-flown schedule which used much of the pre-launch margin before the opportunity to leave the asteroid for Earth return. The sample collection occurred approximately 1 year later than originally planned. Furthermore, after TAG, a Post TAG Observations (PTO) phase, including a Detailed Survey (DS)-Flyby-2-like flyby of Bennu, was added and the asteroid departure maneuver (ADM) maneuver was moved to May 10, 2021 based on lower ΔV cost.

Williams, et al.[4] reported on our pre-launch navigation concept of operations (CONOPS), analysis and expected performance. In addition, Antreasian, et al.[5] further discussed the OD filter strategy and expected predict and knowledge S/C state errors for the original ProxOps phases. The TAG design and expected performance is given by Berry, et al..[8] Jackman, et al.[9] explained our OpNav CONOPS. These pre-launch plans and analyses can be compared or contrasted with the following papers that describe our post-ProxOps experience:

- Anteasian, et al.[10] describe the navigation performance on approach.
- Leonard, et al.[11] report on the OD performance during the first segment of Proximity operations known as the Navigation campaign where we transitioned from center-finding OpNavs to landmark tracking and iterated on the Bennu shape model (DTM).
- Wibben, et al.[12] report on the trajectory design, maneuver targeting and execution performance during the Navigation Campaign.
- Wibben, et al.[13] discuss the frozen orbit design used for the Orbital A phase and our flight experience.

- Wibben, et al.[14] report on the trajectory design, maneuver targeting and execution performance during the Detailed Survey.
- Leonard, et al.[15] report on the shape model iterations and performance provided by the Altimetry Working Group (ALTWG) for operations and by Jet Propulsion Laboratory (JPL) Nav for verification.
- Leonard, et al.[16] discuss the OD prediction performance during the entire ProxOps.
- Adam, et al.[17] report on the as-flown OpNav planning conops from strategic planning 3 months before phase execution to tactical planning starting 8 weeks out from weekly sequence execution.
- Levine, et al.[18] report on the 625-m and 250-m Reconnaissance flyover trajectory designs and navigation performance.
- Wibben, et al.[19] explain the orbit trim strategies we employed to either correct the orbit conditions or phase the orbit to accurately achieve the desired orbital location at the desired time.
- McCarthy, et al.[20] cover the landmark OpNav performance.
- Sahr, et al.[21] report on the S/C pointing performance, comparing our Star-based and OD filter estimates of imager boresite to the reconstructed attitude telemetry.
- Berry, et al.[1] report on the as-flown TAG design and performance.
- Anteasian, et al.[2] describe the overall ProxOps navigation conops and navigation performance.
- Getzandanner, et al.[6] discuss the lessons learned from our experience that could inform further small-body missions.

PRE-LAUNCH ANALYSIS

It was evident to the team and to expert peer reviewers during the design phase that exquisite model fidelity and aggressive operational concepts, which challenged and advanced the state of the art for deep space proximity operations, would be required to meet the mission's objectives. Small non-gravitational forces had a significant effect on the S/C trajectory while in close proximity to the low gravity, small, 500-m asteroid. At Bennu, these forces, which include Bennu's infrared radiation and albedo pressure, the S/C thermal radiation pressure (TRP), out-gassing, and solar radiation pressure (SRP) must be modeled and their errors accounted for in the OD predicted trajectories for successful sequence development, science observations, and maneuver designs. The 1-km orbits, like those in Orbital-B, were of particular importance for navigation since these became the 'safe-home' orbit from which the S/C executed the Orbit Departure Maneuver (ODM)s for reconnaissance flyovers, sample collection, and TAG rehearsals. To achieve the main mission objective of collecting the sample, one of the primary FDS requirements (FDS-F-182e, given below) was placed on predicted trajectory performance. Yet, it was difficult to know pre-launch how well the non-gravitational forces could be determined in operations. In the OD filter, a three-axis stochastic acceleration white noise process[4] is typically used to represent the predicted uncertainties of the small unmodeled or mismodeled forces below 10% of SRP with batch intervals of 1–12 hrs. It is this process noise in the absence of maneuver or desat errors, that determines the predicted down-track state uncertainties. The goal is to model these SRP, TRP and other small forces on the S/C and the predicted attitude as accurately as possible in order to minimize these stochastic accelerations. The OD filter we used for our navigation was the Multiple Interferometric Ranging Analysis using GPS Ensemble (MIRAGE) navigation software, which is a pseudo-epoch state batch sequential filter.[22] For ProxOps, we typically used a batch size of 6 hrs.

The pre-launch mission plan was to initiate the sequences for TAG, rehearsals, or reconnaissance flyovers from the 1-km circular orbit of Orbital-B; however, 'safe-home' orbits actually adopted during ProxOps were eccentric frozen sun-terminator orbits in which the ODMs were performed from a distance of 1-km.[19] These included orbits with the semi-major axis ranging from 0.83 to 1.2

Table 1: Level of forces for CP/R, MP/R and TAG

Major Force (acceleration)	Checkpoint Rehearsal April 13-14, 2020 @0.917 au from Sun (nm/s^2)	Matchpoint Rehearsal August 10–11, 2020 @1.26 au from Sun (nm/s^2)	TAG October 19–20, 2020 @1.35 au from Sun (nm/s^2)
Bennu (central body)	4749–8977	4850–8038	4322–8450
Bennu Oblateness	27.6–150.7	23.7–121.8	20.4–133.6
Solar Radiation Pressure	65.2–74.6	33.6–38.4	30.6–34.1
Thermal Radiation Pressure	8.36–10.2	3.85–5.15	3.60–4.48
Stoch. Accelerations	0.28–1.1	0.72–2.26	0.10–1.58
Bennu Albedo	0.29–0.72	0.12–0.31	0.10–0.24
Bennu Infrared	0.21–0.59	0.093–0.23	0.071–0.20
HGA, LGA Antenna Pressure	0.22–0.24	0.22–0.24	0.22–0.24
Sun (third body)	0.039–0.052	0.015–0.020	0.012–0.017

km and eccentricities ranging from 8 to 17 percent. Table 1 compares the reconstructed major forces acting on the S/C in the prediction span from the tracking data cutoff to ODM for Checkpoint Rehearsal (CP/R), Matchpoint Rehearsal (MP/R) and TAG. Many of these forces were refined during ProxOps.[11,16] Geeraert, et al.[7] describe the effort made in modeling these forces, including using an accurate ray-traced SRP model of the S/C rather then the original 10-plate model.[5] The spherical harmonic gravity field of Bennu to degree and order 9 was determined from particles found in orbit about Bennu from particle ejection events.[23–25] As shown in Table 1, the antenna radiation pressure resulting from the radio signal transmissions radiating from the High Gain Antenna (HGA) and Low Gain Antenna (LGA) were also notable forces while in ProxOps.[7]

The sample collection approach was designed around the capability to deliver the spacecraft to any point on the surface within 25 m (98.3%) of the specified target (FDS-F-13, MRD-13). In the time-frame leading up to the mission Critical Design Review (CDR) in early 2014, navigation performance margins relative to this 25-m requirement received significant scrutiny from within the project and from external reviewers. The assumptions used in our ProxOps navigation error analysis for the orbit departure state uncertainties, where the ODM initiated the TAG descent, rehearsal or reconnaissance trajectories, were an important contributor to the ability to meet the delivery requirement for TAG.

Departure navigation uncertainties needed for reconnaissance flyovers, rehearsals, and TAG were specified in FDS requirement FDS-F-182e, flowed down from the Mission Requirements Document (MRD) (MRD-182e):

> *The FDS shall be capable of satisfying the Orbital Phase B exit criteria allocated to it (as defined in MRD-182), as follows: Tracking data cut-off + 16-hour spacecraft ephemeris predictions are accurate to 4.5 m (3σ) in position, each axis, relative to Bennu.*

The pre-CDR stochastic acceleration model used in the ProxOps analyses assumed an error at the level of 2–3% of SRP (1 nm/s^2). But in subsequent analysis, it was then determined that the level of these non-grav errors needed to be an order of magnitude lower (0.1 nm/s^2) in order to satisfy the FDS-F-182e prediction requirement of 4.5 m (3σ). The Monte Carlo (MC) TAG delivery analysis results presented at the Engineering Peer Review (EPR) as baseline sampled the state knowledge

covariance using this lower error value. It was reasoned that in operations the non-grav errors could be well calibrated from repeated overlapping OD data arcs well ahead of a sortie or sampling event. The results showed the TAG delivery requirements being met with significant margin. Nevertheless, reconstruction of these non-grav errors would require a very high level of fidelity in modeling, and could only be accomplished if S/C activities were extremely quiescent leading up to the departure burn. As such, a MC TAG delivery analysis used initial "inflated" navigation state errors more consistent with the 1.3–3.0% SRP level. Results from this MC analysis were shown to meet the TAG requirements with margin; however there were still concerns that these uncertainties might be too optimistic, so the team invested considerable effort to examine the small forces in more detail.[7,11,16]

In the OD covariance study, stochastic acceleration errors were found to be reconstructed to below the 2 nm/s^2 level in the sunward direction and below 0.1 nm/s^2 in directions orthogonal to the Sun throughout the data arc which included landmark measurements with a two-hour cadence. To first order, this demonstrated the ability to adequately reconstruct the non-grav errors in operations and to scale the predictive non-grav force models appropriately.

To determine the threshold state errors that met the TAG requirements, the state covariance at the time of ODM representing the 1 nm/s^2 stochastic acceleration error was scaled up by 10. The results of the MC analysis for this case showed the TAG delivery errors met the requirements in all cases with margin. This scaled state covariance closely corresponded to a scaling on the process noise by a similar amount, 3 nm/s^2, which represented non-grav errors at 5–9% SRP. The Orbital-B OD covariance study was repeated with this process noise and the MC TAG delivery analysis was redone to ensure the assumptions in the OD filter still met the TAG delivery requirements. The state errors from the updated OD covariance study and the TAG delivery errors were in close agreement to those from the scaled covariance. The 3-σ radial, transverse and normal state errors at time of ODM were, respectively, 20–24 m, 53–76 m and 3.3–3.9 m. With these state covariances, the resulting TAG delivery errors from the MC ranged from 16–21 m which showed margin relative to the 25-m requirement. With these results and the capability of the OD filter to reconstruct these stochastic errors below 3 nm/s^2, we proposed to set the per-axis stochastic process noise to be 3 nm/s^2.

As a result of this work, the Orbital-B state uncertainty requirement at the time of ODM was rewritten as, FDS-F-656 (MRD-656),

> *OSIRIS-REx shall predict spacecraft position in Orbital B such that predictions 24 hours after OD cutoff agree to the current (definitive) position estimates to within 20, 85, and 7 meters (goal - 6, 24, and 5 meters), all 3-sigma values, in radial, along-track, and cross track (orbit-normal) directions, respectively.*

DEVELOPMENT EFFORTS TO IMPROVE NAVIGATION

During the pre-launch development phase, the navigation team found that the required S/C errors set by LM S/C team for momentum desaturation (desat), maneuver and pointing errors to be limiting our performance. As such, the NASA Goddard Space Flight Center (GSFC) project office allocated resources for LM to conduct special studies to revisit some verification analysis and determine current best estimate (CBE) levels on the following: S/C pointing errors, momentum management and desat strategies, Attitude Control System (ACS)-Turn-Burn-Turn (TBT) and vector burn execution errors.

Operations Planning Improvements

In planning science operations, steps were taken pre-launch to adjust the mission CONOPS and activity timelines to mitigate possible sources of error. Flyby trajectories were designed in consideration of the science observation tolerances to account for which components of the trajectory would have the largest errors. Science activities were designed to occur as soon as possible following the propulsive maneuvers to target the desired observations to minimize the time over which maneuver execution errors could propagate, and with OD data cutoff (DCO)s placed before the observations in order to update the asteroid-relative pointing. OpNav observations were carefully scheduled to minimize the time between shuttering of the last image and the downlink of daily images which kicked off the OD processing, and care was taken in the placement of weekly desats such that they would be reconstructed in the OD solution prior to the next observation.

Attitude Prediction Improvements

During pre-launch discussions with the LM GNC team, it became clear that the standard process for generating attitude predictions would not be adequate, due to the fact that predictive errors in the trajectory grew to be large with respect to Bennu's radius in just a few days. In order to have good down-track predictions, the navigation team would have to generate the attitude predicts themselves based on the various planned S/C configurations for ProxOps and a baseline schedule of planned HGA passes (slew HGA (+$X_{S/C}$ axis) to Earth point) and OpNav-nadir pointing (+6° towards Sun).[9] The down-track prediction accuracy depends on the accuracy of the modeling magnitude and direction of the forces on the spacecraft. The GNC team could only produce these predicts late in the operations process as discussed by Leonard, et al.[16] with no time for iteration in the '24-hr' late updates (maneuver or ephemeris). At 3 weeks out from weekly sequence execution, the GNC team would produce the weekly attitude based on the inputs from Nav (including reference trajectory, maneuver, tracking and OpNav requests). Because of accumulation of down-track errors, these attitudes would become stale as we moved through operations. As discussed in detail in Reference 16, because the thermal force is a significant force on the S/C at close range to Bennu and it depends on the solar radiation flux on each surface, the thermal model needs to iterate with the S/C attitude to correctly model its effect on the S/C trajectory.

Momentum Desaturation Maneuvers

The desat maneuvers which used balanced ACS thruster couples, were performed once or twice weekly in ProxOps to desaturate the momentum accumulation on the reaction wheels. The 3-σ desat requirements stated that the S/C shall impart ΔV less than 1.5 mm/s (3-sigma) along each S/C axis for desats after 3 days of momentum growth and less than 6.0 mm/s (3-sigma) for desats after 10 days of growth. As described below, we found the perturbations from desats in practice to be much smaller than this.

The effects from desats were mitigated by ensuring their execution scheduled with both OpNavs and radio metric tracking data bracketing execution if possible before the OD tracking DCO to reconstruct their performance before critical late update deliveries. The last OpNav image was scheduled to be taken closest to the start of the HGA pass to minimize the predict time span of the OD from DCO to maneuver execution or science observation. In addition, the LM Guidance, Navigation, & Control (GNC) team developed two strategies to mitigate their effect on our OD predictions or minimize the ΔV during desats: 1) bias desats, which biased the angular momentum accumulation to provide longer period before reaching thresholds, 2) mask one of the axis, which

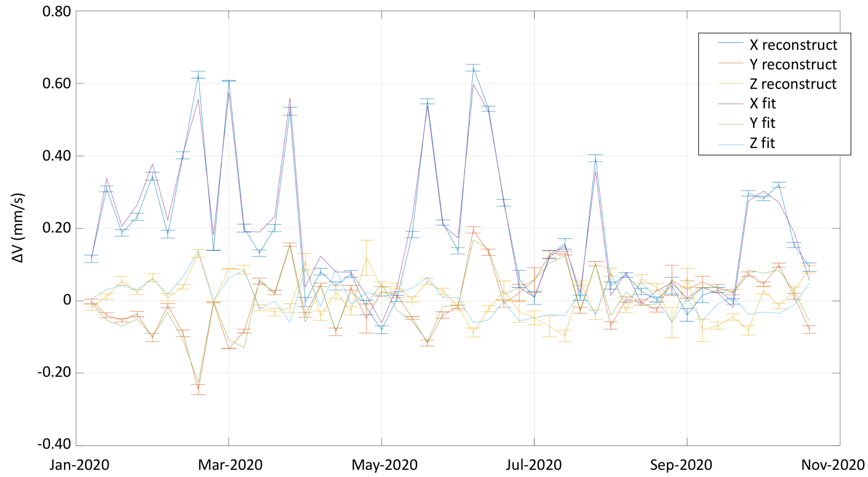


Figure 2: Reconstructed desat ΔV components compared to predicted values

would avoid desaturating the reaction wheels about the $Z_{S/C}$ body axis, thereby minimizing the imparted ΔV. The biasing allowed us to avoid desats during several days of busy maneuver and science observation activities. Masking allowed the S/C team to schedule these before science observations with minimal effect on our trajectory predictions. Because of the orientation of the ACS thrusters which had less torque authority about the Z axis, the momentum accumulated about this axis required significantly more thruster firings. This momentum could then be transferred to another axis for desaturation later if necessary. LM employed these techniques in the Preliminary Survey and Detailed Survey mission phases.

For ProxOps OD solutions through Reconnaissance A ending in late October 2019, it was assumed that the desat *a priori* ΔV values were zero. In reality, the estimated ΔV magnitude of desats ranged from 0.1–1.5 mm/s. Landmark tracking enabled each component of the desat to be reconstructed with post-fit errors $<$0.1 mm/s.

Occasionally, it was impossible to acquire post-desat OpNavs; these data were crucial to reconstruct desat errors well enough to ensure state predictions meet requirements 24–33 hours after a critical delivery. It was found that in the presence of the dynamic environment of Bennu, that radio metric only reconstructed desats often failed to represent the correct ΔV magnitude or its direction. Therefore, through carefull planning with the S/C team, OD solutions without OpNavs covering the last desat before the tracking DCO were avoided for the late update maneuver designs or science observations. However, this could not be avoided for several onboard ephemeris late updates. These solutions affected the pointing of the OpNavs, but these images and their quantity were planned with conservatism such that occasional missed or clipped images of the asteroid in a few OpNavs would not impact the OD performance.

It was difficult to predict the resultant ΔV of these events until the S/C repositioned the solar arrays with inner and outer gimbal angles at 90°, 20° in during Orbital-B beginning mid-June 2019. At this orientation, the LM GNC team noticed a trend associated with the desat ΔV estimates in the S/C body frame and the more active thrusters. It was determined that thruster plume impingement on the solar panels in this orientation with certain ACS thrusters could impart ΔV in the X and Z body axis. As described by Leonard, et al.,[16] this led the development of a least squares filter to determine the ΔV per pulse for each of the eight ACS thrusters using the reconstructed values as the observables. Leonard, et al.[16] further explained that these ΔV per pulse per thruster estimates

were used to reliably predict the ΔV of future desats using the predicted thruster counts given to Nav by the GNC team in the predicted Small Force File (SFF)s. Figure 2 compares the predicted (fit) desat ΔV body-fixed components to the reconstructed values. It was found that these predicts were accurate to 0.033 mm/s (1σ) per axis.[16]

Figure 3 compares the reconstructed ΔV estimates per S/C body axis for all desats during ProxOps to the 3-day 3-σ requirement. Notice, the 7-day requirement is not shown. The red data refer to desats performed after 1–6 days of momentum accumulation, whereas the blue data represent desats performed after 7–12 days of momentum accumulation. During the Orbital-A and Detailed Survey phases, two desats were scheduled, then for most of the remainder of ProxOps, 1 desat per week was scheduled. Note all desats performed within the 1.5 mm/s 3-day 3-σ requirement, suggesting this requirement too conservative and the 7-day requirement unnecessary. As discussed by Leonard, et al.[16] the desats during Orbital-A were determined with 1-σ magnitudes of 0.045 mm/s. The excellent, quiet performance of the S/C during desats was in part due to significant margins realized with respect to elements of the GNC error budget, such as thruster mis-allignments, S/C CG offset, etc. However, some of the operational strategies described above also contributed to realizing smaller perturbations.

Stochastic Accelerations

Figure 4 compares the stochastic accelerations in the 3 body-fixed axis to the pre-launch covariance analysis, initial ProxOps, and post-Navigation Campaign *a priori* errors used in the OD filter. Over the entire ProxOps, the estimated stochastic accelerations had 1-σ errors of 0.54 nm/s^2 in X, 0.075 nm/s^2 in Y and 0.48 nm/s^2 in Z. This plot demonstrates how well the non-grav models including SRP and TRP were improved. The pre-launch 3 nm/s^2 acceleration represented SRP errors from 3.9–8.8% with SRP magnitudes ranges from 34–78 nm/s^2. These estimated acceleration errors reduced the errors to 0.7–1.6% of SRP.

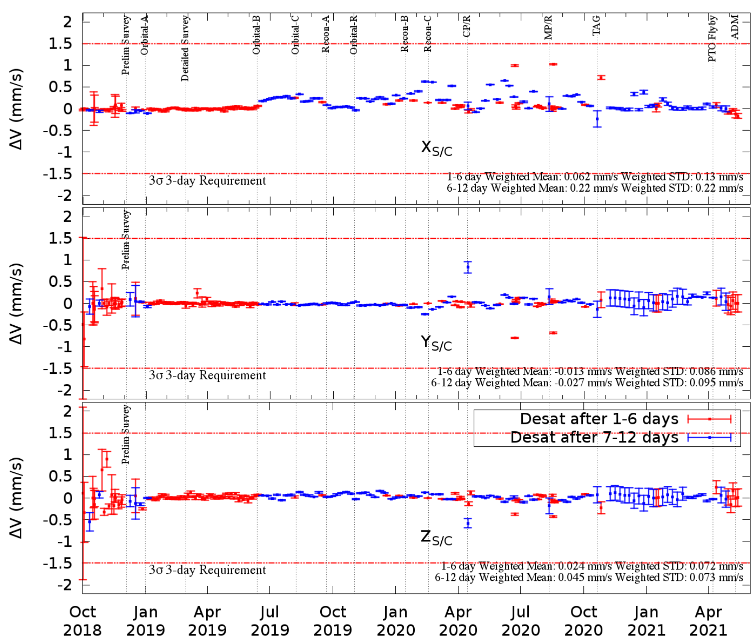


Figure 3: Comparing desat ΔV estimates in the S/C body-fixed axes to the 3-day desat requirement

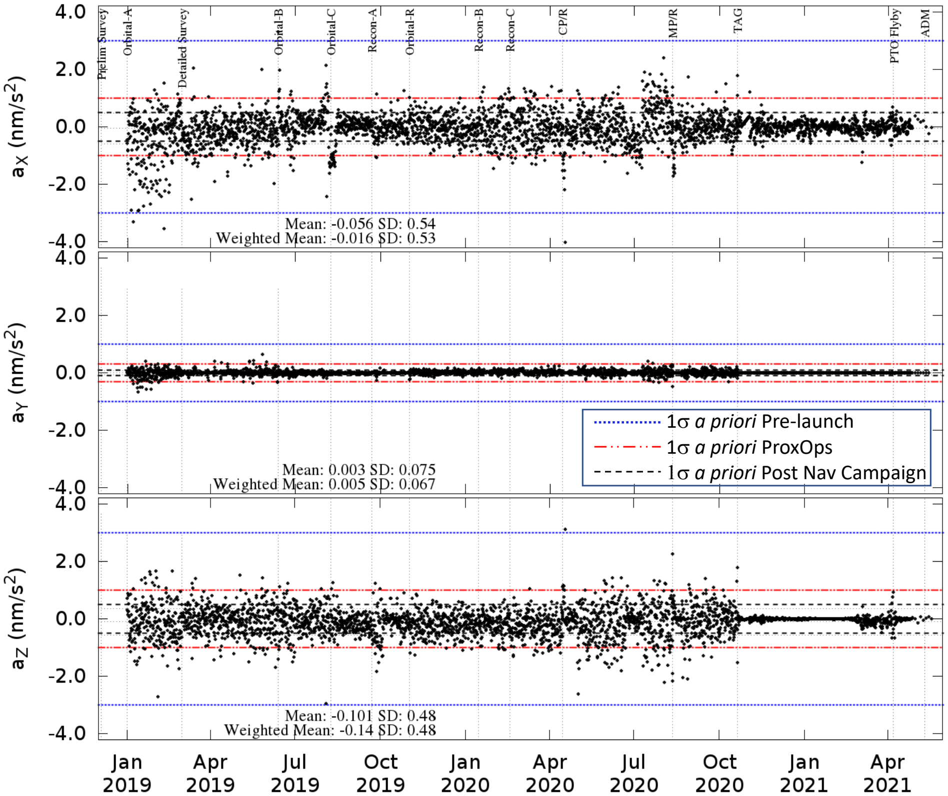
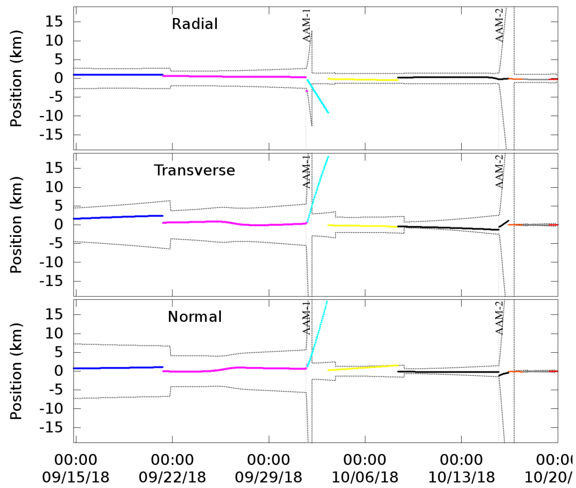


Figure 4: Comparing stochastic acceleration estimates in the S/C body-fixed axes to 1σ *a priori* pre-launch, ProxOps and after Navigation Campaign

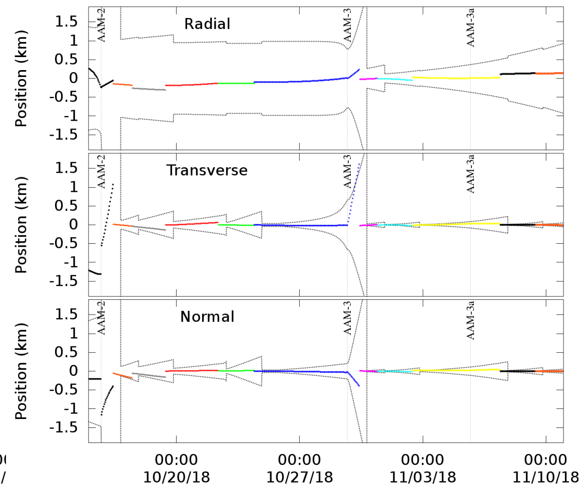
RESULTS–COMPARING PRE-LAUNCH NAVIGATION ERRORS TO PROXOPS

Approach

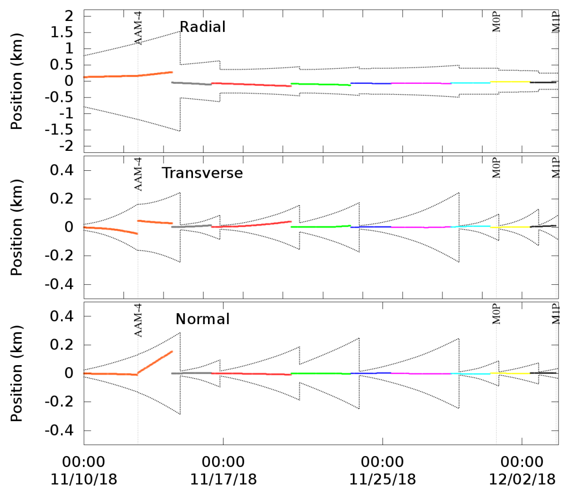
Figure 5 compares the reconstructed trajectory errors of the approach OD solutions to the 1-σ pre-launch errors. These pre-launch errors appear to be farily conservative. Only one solution was found to exceed these 1-σ errors, which was the OD solution immediately after AAM-1, where this solution used radio metric data only immediately after the maneuver execution as what was assumed in the pre-launch covariance study. The two hours of post-AAM-1 radio metric tracking data was insufficient to estimate the burn precisely enough. More details of the Approach navigation performance was reported by Antreasian, et al.[10]



(a)



(b)



(c)

Figure 5: Comparing reconstructed Bennu Approach trajectory to 1-σ Pre-launch covariance analysis.

Preliminary Survey

Figure 6 compares the determination of the Bennu GM (gravitational parameter) from the operational solutions during the Preliminary Survey (PS) through the Orbital-A insertion to the pre-launch study. Although, the *a priori* GM uncertainty of the pre-launch study assumed 100% to the 10% error in operations, the significant improvements of the ops solutions over the pre-launch results was due to the OD filter change in the ops solutions. These solutions did not include stochastic accelerations in the OD filter which reduced the GM post-fit errors significantly over the pre-launch.

Figures 7(a–e) compare the reconstructed PS trajectory errors during the three North pole flybys, Equator, and South pole flybys to the the 1 and 2-σ errors from the pre-launch covariance studies. The trajectory errors during the science observations at closest approach (C/A) ranged from less the 1 σ to just over 1 σ. Although the pre-launch covariance study was performed on the original 1-North pole PS design, these pre-launch errors are consistent to the post-launch errors and are at

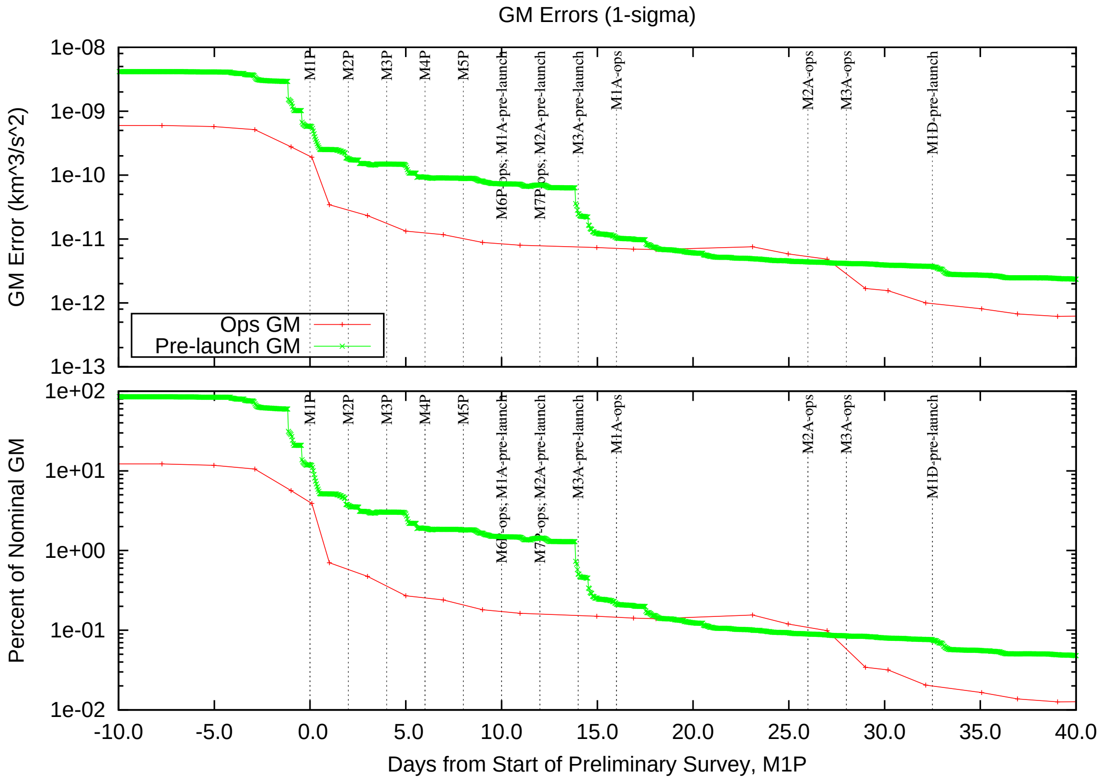
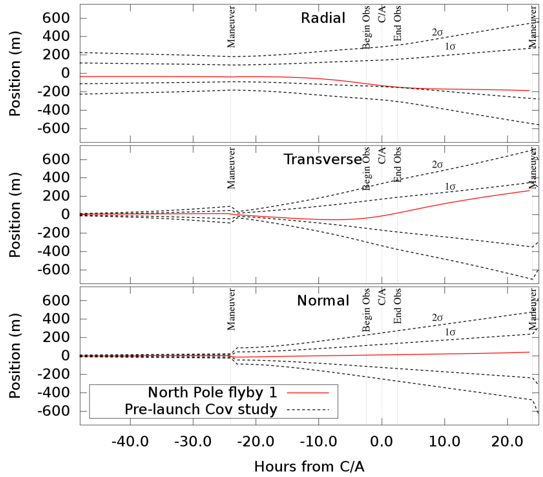
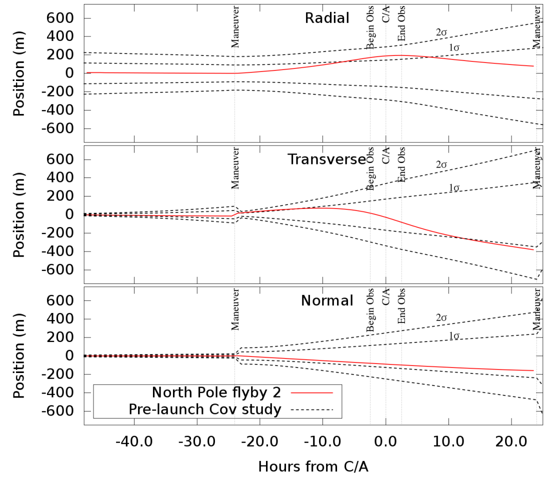


Figure 6: Comparing Reduction of GM uncertainty and Resultant Percentage of known mass between Pre-launch and Operational solutions

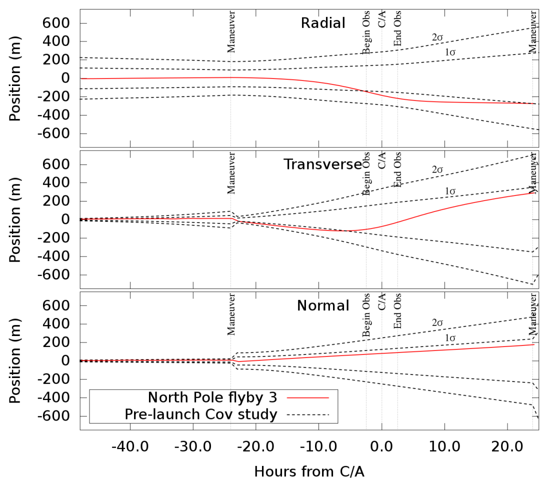
the appropriate level with the results.



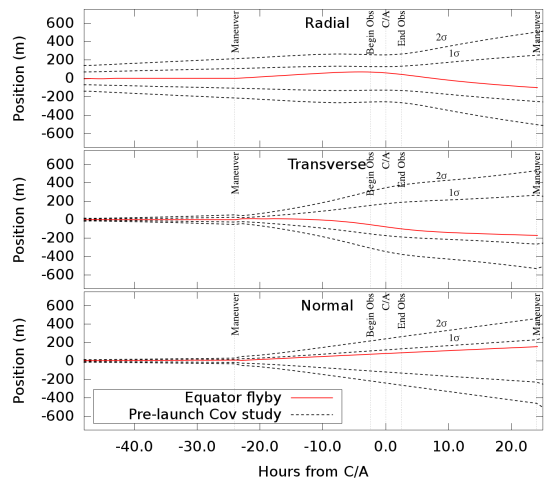
(a) North Pole Flyby 1



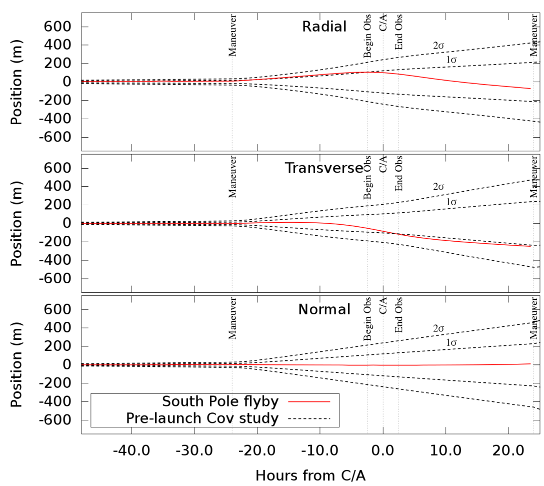
(b) North Pole Flyby 2



(c) North Pole Flyby 3

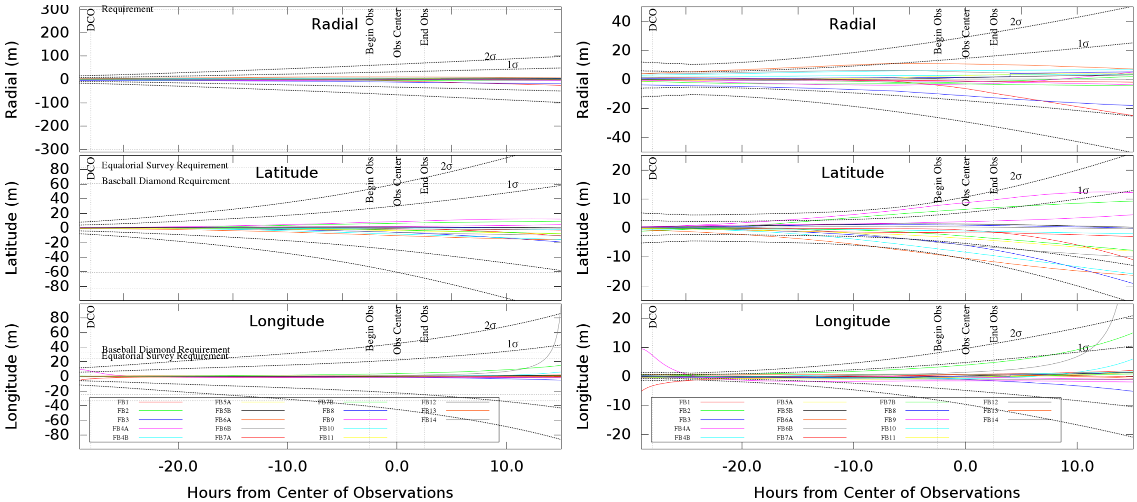


(d) Equator Flyby



(e) South Pole Flyby

Figure 7: Comparing reconstructed Preliminary Survey flyovers to 1-σ and 2-σ errors from the pre-launch covariance analyses.



(a) Comparing to Pre-launch covariance study

(b) Comparing to Post-launch covariance study

Figure 8: Comparing reconstructed Detailed Survey flyovers to pre and post-launch covariance analyses.

Detailed Survey

Figures 8a and 8b compare the reconstructed DS trajectory errors during the 18 science observation flybys, respectively, to the pre-launch and post-launch covariance studies. Though each flyby was unique and produced slightly different uncertainties, these errors were similar enough to use the errors from one of the flybys to represent them all.

Orbital Phases, Predicted State Improvements

Recall in the "Pre-launch" section, the orbital phases, and especially the $\sim$1-km frozen orbits, were of importance for navigation. These became the 'safe home' orbits for initiating the 625-m (mid) and 250-m (low) altitude reconnaissance flyovers of the prime and backup sample collection sites as well as for CP/R, MP/R and TAG. The redeveloped orbit departure state uncertainty requirements were based on an increase in the 3-axis stochastic acceleration process noise. This stochastic acceleration was used to predict the trajectory uncertainties at ODM and were found to bound the MC TAG trajectory analysis that could meet the pre-launch 25-m TAG delivery requirement with margin.[4] The new requirements allowed the predicted state errors to be within 20 m, 85 m and 7 m (3σ) in the radial, transverse (down-track) and normal directions, respectively. The goal (which was written in these requirements) was to achieve state errors to within 6 m, 24 m and 5 m, in these corresponding directions. This replaced the original 3-σ 3-axis requirement of 4.5 m.

The asteroid's rough and rocky surface meant that there were no candidate sample collection sites anywhere on Bennu that were larger than the 25-m requirement specified pre-launch. A thorough analysis of the surface of Bennu revealed that the largest hazard-free areas on the surface were no greater than about 8 m radius.[26] This prompted the project to adopt the LM Natural Feature Tracking (NFT) algorithm as the prime autonomous onboard navigation method after ODM to update the two decent maneuvers Checkpoint (CP) and Matchpoint (MP), rather than the original simple algorithm using a pair of GNC light detection and ranging (LiDAR) measurements.[1] The NFT algorithm used a Kalman filter to update the S/C state by minimizing the residuals of known feature locations on Bennu from that in the onboard catalog to those correlated in the images from periodic NavCam 2

images during the TAG descent trajectory. MC TAG delivery analysis showed that the use of NFT in conjunction with improved navigation prediction and maneuver execution error performance at ODM relative to what was assumed pre-launch improved the expected 3-σ TAG dispersions from 20 m pre-launch to levels approaching 8 m.[27] Although not formalized as a requirement in the same way as the 25 meter pre-launch TAG requirement, the 8-m dispersion effectively became the new upper bound on TAG performance. The team knew that the navigation prediction performance would need to exceed the revised navigation requirement in order to accomplish a successful TAG within the sites of this size. Figure 9 compares the as-flown 98.3% TAG delivery dispersion (6.4 x 5.1 m) to the 25-m pre-launch TAG delivery requirement and this new 8-m 'ProxOps requirement' overlaid on the Nightingale site.

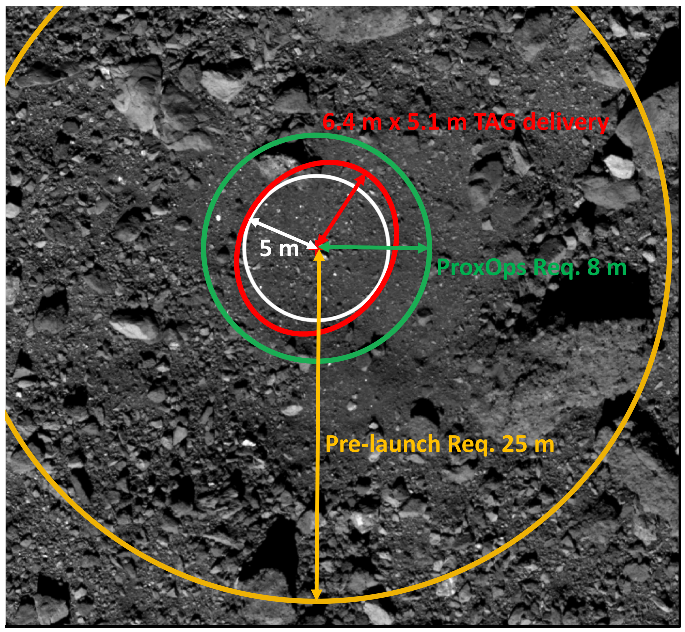
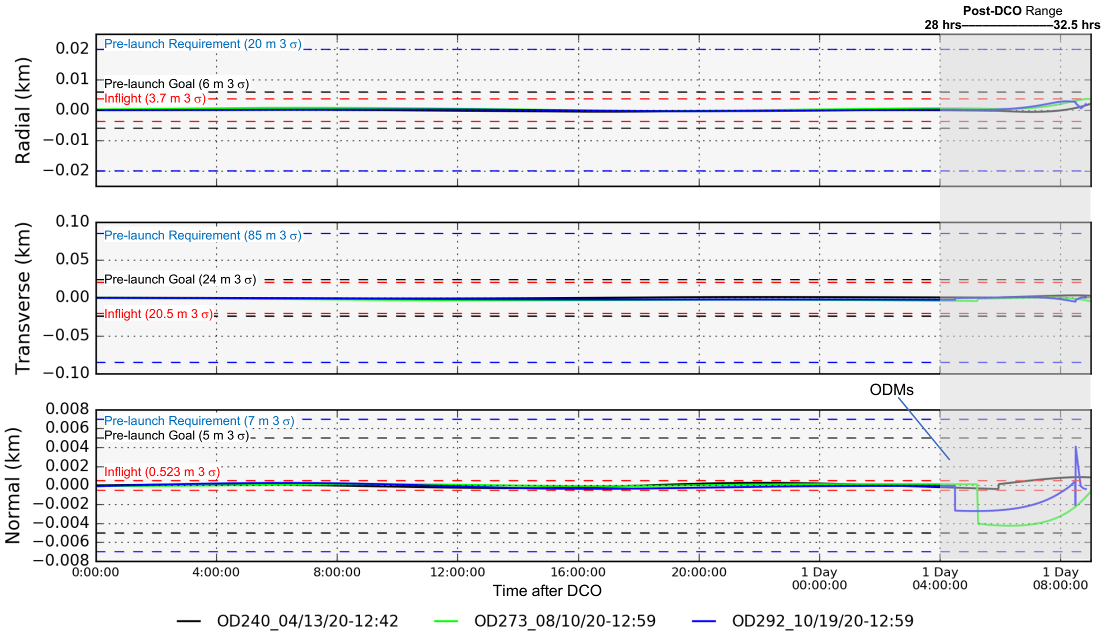


Figure 9: Comparing the TAG pre-launch and ProxOps-NFT requirements to the as-flown 98.3% (6.4 x 5.1 m) TAG delivery error ellipse

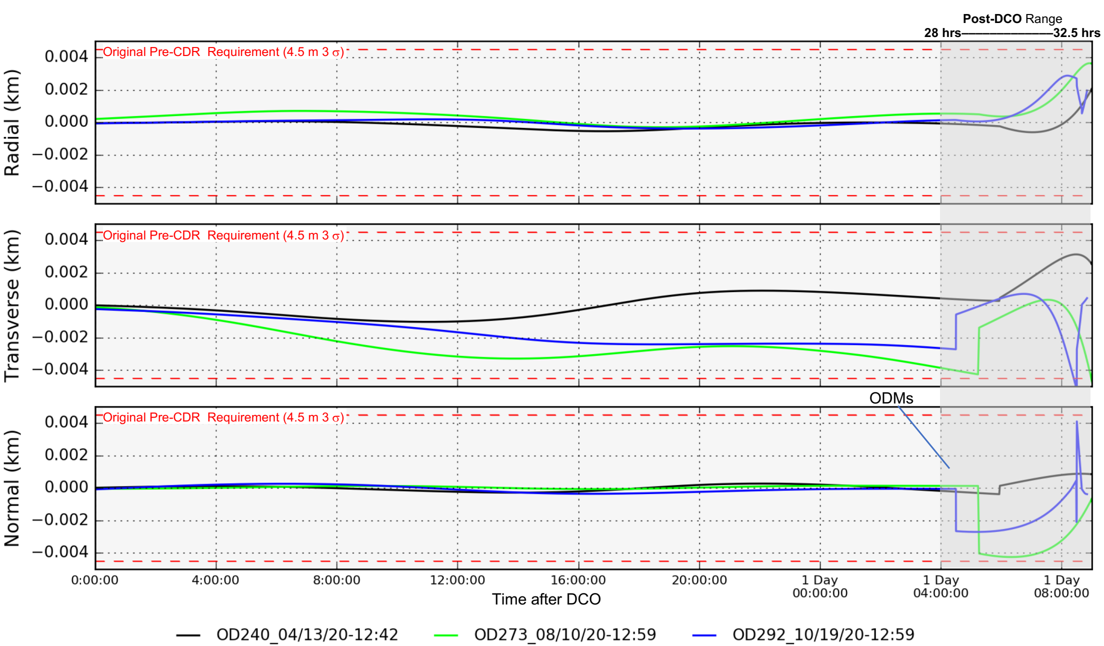
Leonard, et al.[16] discussed the OD prediction performance during all phases of ProxOps. These results showed all Orbital-B OD deliveries (19 total) had 24-hr 1-σ predicted state errors of 0.20 m, 3.2 m and 0.22 m in the radial, transverse and normal directions. In addition, Antreasian, et al.[2] showed that nearly all orbital OD solutions from Orbital-R in November 2019 through TAG in October 2020 (75 total) had 28–33 hr combined 1-σ predicted state errors of 0.84 m, 3.1 m and 0.69 m in the radial, transverse and normal directions, respectively. Note, Orbital-R had essentially the same orbital characteristics as the eventual 'safe home' orbit beginning in January 2020 for the mid and low reconnaissance flyovers, CP/R, MP/R and TAG.

Figure 10a compares the 28–31 hr predicted state errors (in the orbit-fixed radial-transverse-normal components) of OD solutions leading up to the ODM for the CP/R, MP/R and TAG against the pre-launch requirements and goals. Also, these errors are compared to'inflight' goals in red, developed from updated covariance analysis performed during ProxOps, which was based on CBE maneuver and pointing errors in operations. The reconstructed down-track prediction errors from the late update OD deliveries to design ODM and rehearsal or TAG parameters for CP/R, MP/R and TAG were 0.26 m, -4.3 m and -2.7 m, respectively, while the radial and normal errors all were

less than 1 m.[16] Figure 10a demonstrates that the inflight OD predictions were vastly better than the pre-launch requirements and the inflight goals, except in the Normal component, which looked to be close to the in-flight prediction. Finally, Figure 10b shows that in-flight OD predict errors actually met the original 4.5-m 3-σ pre-CDR requirement.



(a) Comparing to requirements, pre-launch and inflight goals



(b) Comparing to original pre-CDR requirements

Figure 10: 28–31 hr OD trajectory predictions during CP/R (OD240), MP/R (OD273), and TAG (OD292) compared. These OD solutions have no propulsive events within the 28–31 hrs time span after DCO.

Checkpoint Rehearsal, Matchpoint Rehearsal and TAG

The onboard NFT filter was initialized with the state covariance at ODM for CP/R, MP/R and TAG. Then NFT filtered images were taken during the post-ODM trajectory to estimate the state and update the CP and MP vector burns. After MP, NFT continued updating the state to determine if the S/C would touch down on a hazard. If a hazard was detected, the descent would be aborted and the back-away burn would move the S/C away from Bennu. Figure 11 compares the results of the propagated locations from CP/R and MP/R to the TAG touchdown location. The hazard map on Nightingale is shown with red and yellow areas. The largest circle surrounding the Nightingale site is 10 m in radius. Also shown, is the 8-m ProxOps requirement and the 6.4 x 5.1 m 98.3% TAG delivery dispersion as computed from the MC TAG analysis using the late update state covariance and expected ODM maneuver execution errors. The white, blue and magenta points and ellipses in the CP/R and MP/R plots represent the predicted contact point and error dispersions propagated from just after the CP burns for CP/R and just after MP burns for MP/R to the surface. For CP/R, the onboard estimates for the MP vector burns are used in the propagation. The white ellipses represent the last NFT onboard state estimate and error mapped to the surface. The blue dots and ellipses represent touchdown locations and dispersions from a navigation MC analysis using the last NFT state and covariance as initial conditions and expected maneuver errors for ODM, CP and MP.The magenta dots and ellipses represent the reconstructed OD and covariance. This Figure shows the touchdown location progressively came closer to the target with each event from 2.2 m for CP/R to 1.7 m in MP/R and finally 0.98 m for TAG. As shown, the TAG delivery was well within the pre-launch requirement.

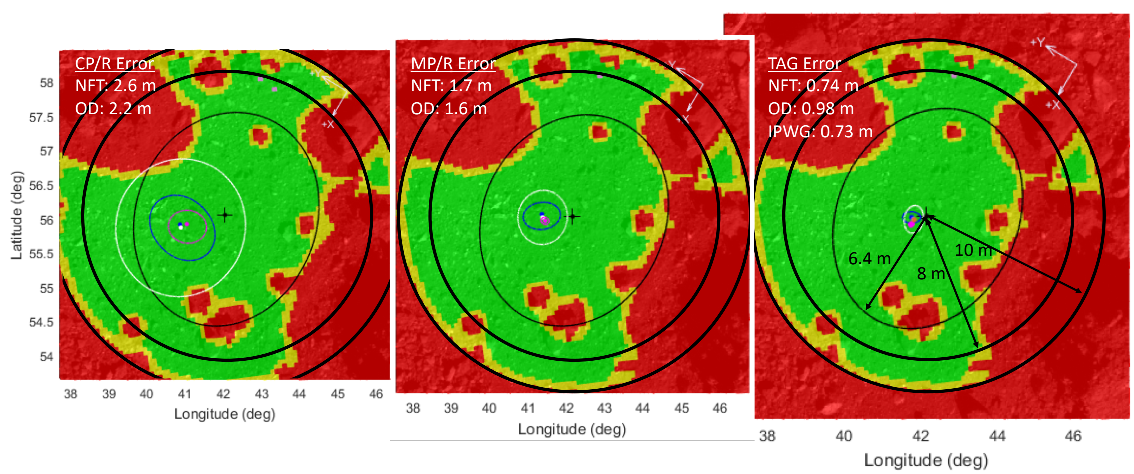


Figure 11: Comparing the propagated CP/R, MP/R to surface contact errors to the TAG delivery error overlaid on the Nightingale hazard map

CONCLUSION

This paper described some of the analysis performed before launch and during operations of the OSIRIS-REx mission to validate expected navigation prediction accuracy and verify the capability to deliver the spacecraft to the surface within 25 meters of the targeted TAG (sample collection) site on the surface. Also discussed are important spacecraft performance factors contributing to navigation prediction performance such as maneuver execution errors and perturbations from momentum

desaturations. Comparisons are made between pre-launch analysis, updated analysis performed during the mission, and actual performance realized in flight. Requirements to operate in close proximity to a small asteroid such as Bennu and ultimately contact the surface levied extremely challenging trajectory prediction requirements on the navigation team. Reviewers during the Critical Design Review phase strongly challenged the team's assumptions about the modeling fidelity that could be achieved at Bennu, which resulted in the adoption of more conservative assumptions in pre-launch analysis. After launch, both the navigation team and spacecraft operations teams revisited analysis to determine where improvements could be realized. The spacecraft team adopted some special procedures for conducting momentum desaturations with thrusters that reduced perturbations to the trajectory. They also removed some conservatism in analysis of maneuver execution error performance. The navigation team began an extensive effort to develop high-fidelity models for small forces acting on the spacecraft and advised the project on operational changes that could be made to reduce the affect of navigation errors on science activities. After OSIRIS-REx arrived at Bennu, the extremely rocky surface meant that the largest candidate sample collection sites were less than 8 meters, much smaller than the 25 meter requirement the system was designed for. The project modified the onboard navigation approach for TAG, implemented new hazard avoidance capabilities onboard the spacecraft, and challenged the navigation team to improve navigation prediction performance even further. The paper presents actual trajectory errors realized at different points in the mission compared to performance predicted from analysis. Extensive cross-references are provided to other works that detail the efforts behind improvements in navigation performance implemented over the course of the mission. In the end, the spacecraft was delivered to the surface of Bennu within less than one meter of the targeted contact point, and navigation predictions leading up to TAG were well within all performance expectations, even beating the arguably optimistic performance specification from the pre-CDR timeframe.

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